Design and operation of domestic hot water systems: optimisation using building energy simulation

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***Abstract* — Achieving energy savings in buildings is important to restrain global warming and attain the targeted reduction of CO_2-emissions. Nowadays, in well insulated and airtight buildings, Domestic Hot Water (DHW) production accounts for 50% of the total heating demand, due to unaltered high production temperatures which ensure *Legionella*-poor DHW systems. In order to address and study this issue, Dymola simulation models, representing a BBRI test facility and a chosen case study apartment site, are developed, which allow to examine *Legionella pneumophila* proliferation risks in DHW systems. The findings are utilised to quantify the effect of renovation measures on infected systems.**

Keywords: *Legionella pneumophila, Domestic Hot Water, Building Energy Simulation & Validation, Energy saving potential and biologic analysis*

INTRODUCTION

Legionella bacteria are innately present in water, albeit often unaltered in nearly undetectable concentrations due to mainly detrimental outdoor conditions. In hydraulic installations however (*e.g.,* DHW systems), favourable conditions occur which stimulate *Legionella* growth. Therefore, DHW is generally produced, stored and distributed at temperatures above 55-60 °C to mitigate the risk of *Legionella* contamination of DHW systems (Stout *et al*., 1986 [1]). Individuals, exposed to high *Legionella* concentrations can suffer from severe pneumonia and even death can occur.

Accordingly, high energy use for DHW is required, which starts to represent an important share in the total energy demand of well insulated and airtight buildings (*Figure 1*). So far on building level, research focussed on the building envelope (*e.g.,* insulation, water-tightness, air-tightness), technical installations (*e.g.,* ventilation, heating, cooling, renewable energy, energy recovery, water (re-)use and recyclability) and architectural design principles. Energy use for DHW systems in residential buildings remained nearly unaltered and has experienced little innovation in the past decennia.

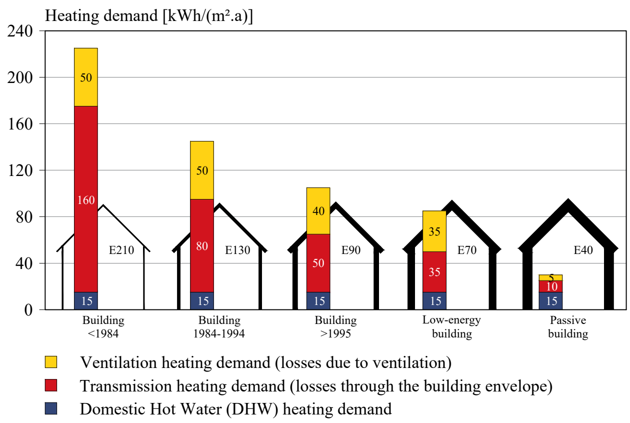

Figure 1 *- Comparison of the heating demand for residential buildings of different age and energy efficiency level (adapted from IKZ-HAUSTECHNIK [2]). Data are obtained in Germany for a detached, single-family house (3 to 4 occupants), with a surface area of 150 m² (A/V = 0.84).*

Building Energy Simulation (BES) models can be of importance in the design and optimisation of such buildings. System simulation models are developed, by which energy-saving measures can be compared, based on decreasing *Legionella pneumophila* contamination risk and improving comfort. The aim is to enable utilisation of such models in the design stage as well as to assess various optimisation measures during the operational stage of sanitary systems (*i.e.*, renovation measures). DHW system designers will be able to reduce energy demand for DHW production, while keeping an equilibrium between energy efficient, comfortable and healthy buildings

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METHODOLOGY

This research is divided into two work packages. First and foremost, experience in BES and sensitivity analyses is gained by composing accurate simulation models, representing a BBRI test facility, in Modelica Dymola. A Modelica simulation model is compared with measured data of a BBRI test facility (*Figure 2*) in order to examine how domestic hot water systems can be composed, calibrated and validated based on temperature and flow rate measurements (including temperature stratification of the boiler). Afterwards a second calibration and validation is executed, based on provided *Legionella pneumophila* concentrations, by the addition of a *Legionella* growth model in Modelica (Van Kenhove *et al.*, 2018 [3]). In the end, a better understanding of temperature and *Legionella* behaviour in DHW systems was obtained.

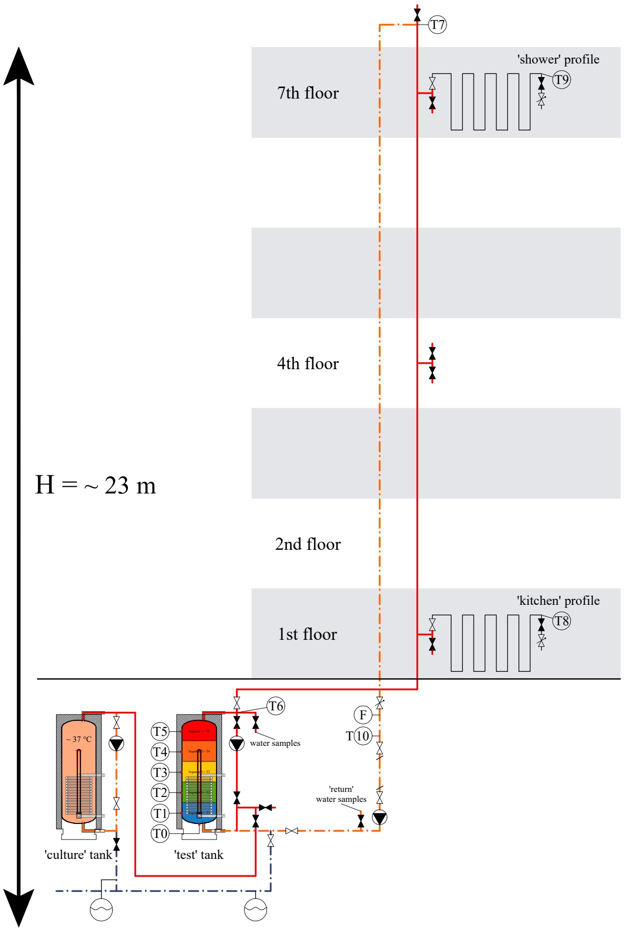

Figure 2 *- Hydraulic scheme of the Legionella test facility (at BBRI [4]).*

Secondly, the validated growth model is used to optimise existing DHW systems in residential buildings. Case study buildings are chosen with occurring *Legionella* issues.

The case study project consists of 4 apartment buildings (block I-IV) with 520 apartments (*Figure 3*) of which both hot and cold water are infected with *Legionella* (*e.g.*, measured DHW temperatures demonstrated in *Figure 4*). A system simulation model of these case-study buildings is developed in Modelica Dymola, based on previously executed water temperature, mass flow rate and *Legionella pneumophila* concentration measurements.

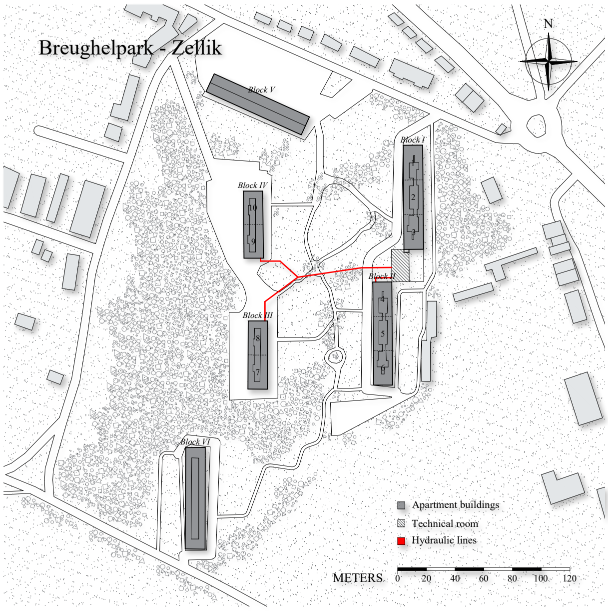

Figure 3 *- Site plan of the apartment blocks, which are located at Breughelpark. The DHW pipes in between the apartment buildings are illustrated by the red lines and verified with a thermography camera.*

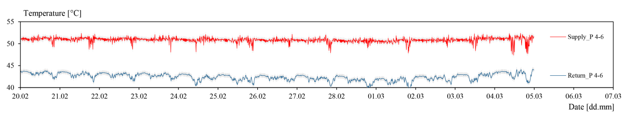

Figure 4 *- Supply and return water temperature to block II (pavilion 4-6). Return temperatures are below 45 °C so Legionella will occur in the system. The accuracy of the logger is 0.21 °C.*

Subsequently, the model is utilised to assess various optimisation measures during the operational stage. The causes of infection of the hot and cold water system and the most effective optimisation/renovation measures, to keep it healthy and energy efficient on the long term, are investigated by simulation. Ultimately, the best suitable measures to adapt the DHW installation are proposed by which energy-saving measures can be compared based on decreasing *Legionella* contamination risk and improving comfort.

RESULTS

For the BBRI test facility, RMSE-values between 0.51 and 2.15 K, MBE-values between -0.010 and 1.199% and CV(RMSE) between 0.158 and 0.734% are achieved for the validation of the thermohydraulic Modelica system simulation model. Furthermore for the *Legionella pneum*. growth model RMSE-values between 435 and 714 cfu/l, MBE-values between -0.000527 and -0.000561% and CV(RMSE) between 0.00069 and 0.00133% are achieved.

Verification of the obtained validation results with calibration acceptance criteria (*Table 1*) justifies that the simulation model can be considered calibrated.

Standard/ Guideline	Monthly criteria [%]		Hourly criteria [%]	
	MBE	CVRMSE	MBE	CVRMSE
ASHRAE [6]	5	15	10	30
IPMVP [7]	20	-	5	20
FEMP [8]	5	15	10	30

Table 1 *- Acceptance criteria for calibration of building energy performance simulation models (Coakley et al., 2014 [5]).*

Given that DHW installations are able to be accurately modelled in Modelica Dymola software as well as calibrated and validated both thermo-hydraulically (*i.e.*, water temperature and flow rate) and biologically (*i.e.*, concerning *Legionella pneumophila* growth), the DHW models can be utilised for existing buildings to determine appropriate renovation strategies.

Three main objectives are explored in the case-study by means of Modelica simulations:

1) Renovation measures to optimise water temperatures throughout the DHW system
2) Renovation measures to keep CW temperatures below 20 °C
3) Verifying if previous best-case renovation measures resolve occurring *Legionella* issues in both domestic water systems

Objective 1

Since only 35% of the 2.8 km of DHW pipes is well or sufficiently insulated, an energy-saving-potential and water temperature analysis by means of adding insulation to uninsulated areas is executed. The obtained results, demonstrated in *Figure 5*, represent the energy savings by decreasing thermal energy losses.

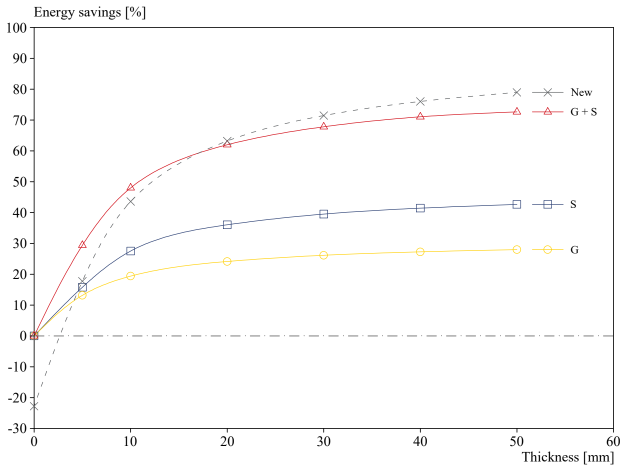

Figure 5 *- Energy savings by adding pipe insulation in the technical shafts (S) of block III/IV (pavilion 7-10), to the uninsulated pipes in the underground (G) or both renovation measures combined (G+S). The grey dotted line represents a scenario in which all existing insulation (35%) is removed and re-insulation is started from scratch (New). The thermal energy savings graph indicates that for 3 cm of pipe insulation, the greater part of potential thermal energy savings is obtained and 3 cm still is a feasible pipe insulation thickness.*

Subsequently, mass flow rates are examined and a system design analysis is executed, which takes the previous findings into account in order to obtain a well considered DHW system design. Simulation results are demonstrated in *Figure 6*.

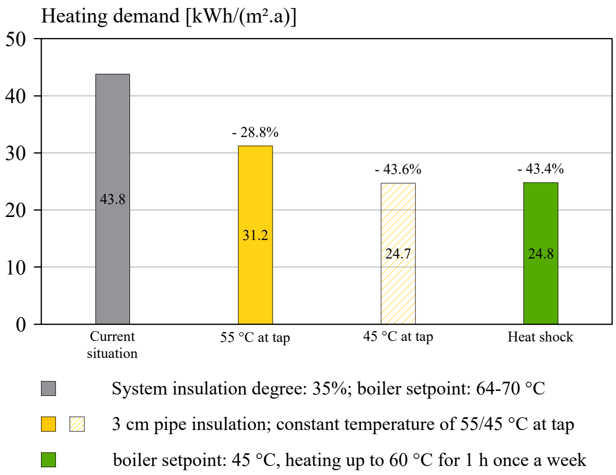

Figure 6 *- Comparison of simulated system optimisation scenarios. Coloured bars (i.e., yellow and green) take 3 cm of pipe insulation, new mass flow rate settings and other boiler recirculation settings into account. Three centimeters of pipe insulation and an improved system design (i.e., the conventional scenario, represented by the yellow bar) account for 28.8% energy savings in comparison to the current situation, higher distributed DHW temperatures and higher temperatures at tapping points. The heat shock regulation (i.e., green bar) accounts for another 20% of energy savings in comparison to the conventional scenario*

Objective 2

DHW and CW pipes are situated together in uninsulated and unventilated shafts (*i.e.,* one shaft supplying the kitchens and one shaft supplying the bathrooms), surrounded by the ambient conditions of two apartments on every floor. The aim of this research question is to make sure cold water temperatures never exceed 20 °C. An additional ventilation flow rate (to keep CW pipes below 20 °C) is utilised to compare the various simulation scenarios in order to find the most cost and energy efficient renovation measure(s) and thus an overall best optimisation scenario. In the new BBT [9] concerning *Legionella*, the BBRI states DHW and CW pipes need to be insulated and located in separate shafts.

Three scenarios were studied, compared and further developed (*Figure 7*).

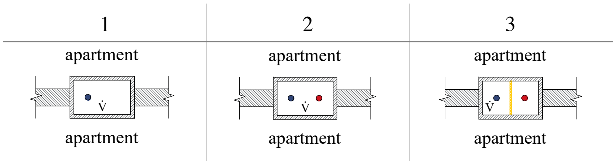

Figure 7 *- Three basic start scenarios, which are studied, compared and further analysed in a CW system optimisation analysis. CW and DHW pipes are displayed, respectively in blue and red. The yellow line represents 3 cm of insulation.*

A summary of the obtained results (in winter conditions) is demonstrated in *Figure 8* and *9*. In *Figure 9*, temperatures in a kitchen shaft at floor level 12 are illustrated since this is the worst-case scenario (*i.e.*, ambient shaft temperatures 'Sh_' and CW temperatures 'L12_') and compared to the tappings of the whole building block to clarify the temperature curves.

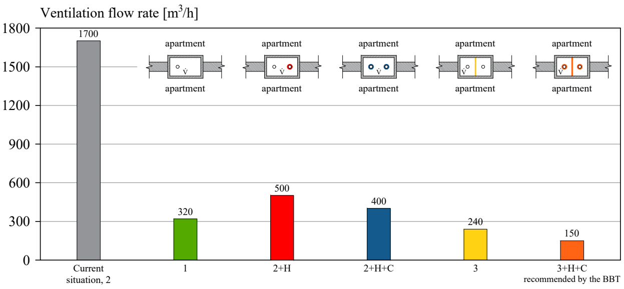

Figure 8 *- Comparison of six CW system scenarios. Scenario analyses demonstrate that the separation of DHW and CW pipes in individual shafts immediately epitomises an enormous optimisation potential since the greater part of transmission, convection and radiation by DHW pipes is blocked immediately. Additional CW pipe insulation (DHW pipe insulation is obligatory) lowers the water temperatures further (orange bar). The scenario recommended by the BBRI proofs to be a best-case scenario.*

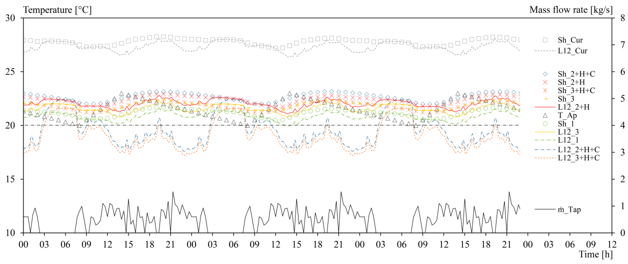

Figure 9 *- Corresponding worst-case cold water and kitchen shaft temperatures for the various scenarios in Figure 8. By adding CW pipe insulation, the water temperatures lower significantly during the greatest part of the day.*

Objective 3

The last research question aims to verify whether the previous proposed best-case optimisation measures also dissolve possible *Legionella pneum.* issues and keep concentrations under control. The risk concentration amounts to 1000 cfu/l. Results for the DHW system are demonstrated in *Figure 10* and *11*, results for the CW system are demonstrated in *Figure 12*. A dead end is inserted to both CW pipes (*i.e.*, kitchen and bathroom).

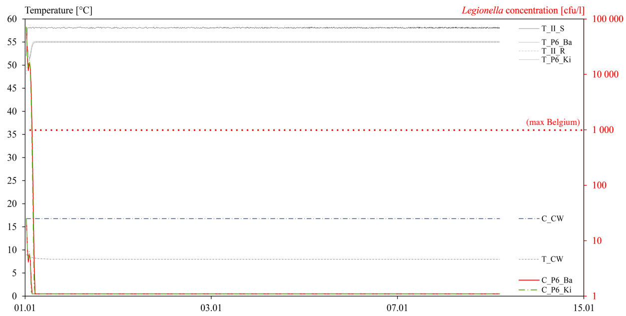

Figure 10 *- Conventional 55 °C regulation in the DHW system (i.e., the energy use is demonstrated in Figure 6 compared to other scenarios). Worst-case Legionella pneum. concentrations are demonstrated in colour (i.e., red and green) on the right ordinate. DHW temperatures are demonstrated in black and grey on the left ordinate. The 55 °C-at-tap regulation proofs to be sufficient to keep Legionella pneum. concentrations under control and for disinfection of the DHW system.*

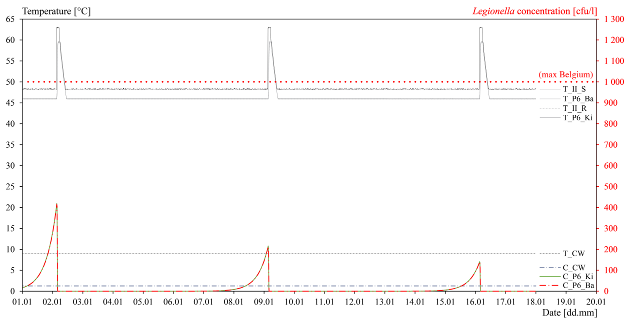

Figure 11 *- Heat shock regulation in the DHW system (i.e., the energy use is demonstrated in Figure 6 compared to other scenarios). Worst-case Legionella pneumophila concentrations are demonstrated in colour (i.e., red and green) on the right ordinate. DHW temperatures are demonstrated in black and grey on the left ordinate. Heat shocks once a week proof to be sufficient to keep Legionella concentrations under control.*

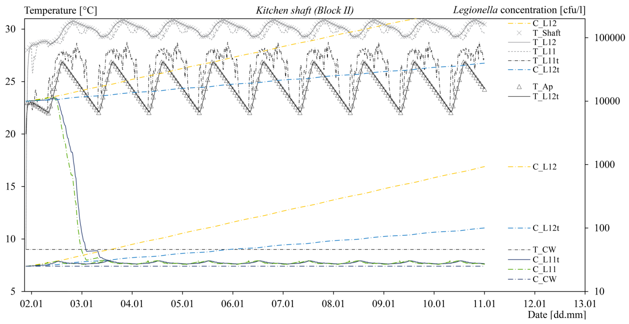

***Figure 12** - Domestic CW system in summer conditions for the kitchen shaft. Temperatures of the worst-case areas in the current system (i.e., floor level 12 in the shaft supplying the kitchens), are demonstrated with corresponding Legionella pneumophila concentrations (in colour, preceded by the character 'C'). DHW temperatures are demonstrated in black and grey on the left ordinate.*

Apparently in the current CW system, *Legionella pneumophila* is not able to grow up to critical concentrations in frequently used CW pipes (in a 9-day simulation). CW sample measurements confirm the low *Legionella* concentrations, but other *Legionella species* were measured, *Legionella pneum.* did not occur. At last, *Legionella pneum.* proliferation occurs in dead pipe ends, which can contaminate the system on the long term.

DISCUSSION AND CONCLUSIONS

Simulation models of domestic water systems (*i.e.,* DHW and CW) can be developed and have the potential to be of great importance in the design, renovation and optimisation of (residential) buildings. Even storage tank stratification can be calibrated and validated, which is proved in a test facility analysis, both thermo-hydraulically and biologically.

For the BBRI test facility, RMSE-values between 0.51 and 2.15 K, MBE-values between -0.010 and 1.199% and CV(RMSE) between 0.158 and 0.734% are achieved for the validation of the thermohydraulic Modelica system simulation model. Furthermore for the *Legionella* growth model RMSE-values between 435 and 714 cfu/l, MBE-values between -0.000527 and -0.000561% and CV(RMSE) between 0.00069 and 0.00133% are achieved.

In case the Modelica software is applied to a *Legionella*-contaminated case study (Breughelpark) analysis, objective 1 demonstrated that energy savings can be obtained in the DHW system by adding 1-3 cm of pipe insulation. For the conventional 55 °C-at-tap regulation with 3 cm of pipe insulation and modified mass flow rates, 28.8% less energy use and much higher DHW temperatures (currently: 36.5-47.0 °C; new: 55 °C everywhere) at taps are obtained in comparison to the current situation. The heat shock regulation corresponded even to 43.4% less energy use and 45 °C at tapping points.

The cold water system analysis (*i.e.*, objective 2) demonstrated that separating DHW and CW pipes is of great importance in order to keep the CW below 20 °C (*Legionella* is in dormant stage below 20 °C). Just as the BBT states, CW insulation can be added, which will lower the CW temperature 3 to 4 °C during the greatest part of the day.

When these best-case optimisation measures are evaluated in terms of *Legionella pneum.* concentration, the DHW conventual 55 °C-at-tap regulation shows no alarming *Legionella pneum.* concentrations. The heat shock regulation also proofs to be suitable when one heat shock is executed every week. The CW system proofs to be safe in the current situation. Although in dead pipe ends, *Legionella pneum.* proliferation occurs, which can contaminate the system in time, but this is not perceived in a 9-day simulation.

In conclusion, the obtained results proof that the Modelica growth model can assist HVAC designers to quantify and decrease the *Legionella* infection risk in the design phase as well as to optimise existing DHW and CW systems. Furthermore, Modelica models are able to reduce the thermal energy use drastically by testing various scenarios (*e.g.*, up to 43.4% in the case study) in existing DHW systems.

FUTURE RESEARCH

By the end of this thesis, the simulation model, which represents the test facility, is considered calibrated and validated in terms of *Legionella pneum*. between the setpoint temperature of 45 °C and a heat shock temperature of 60 °C. Given the importance of the correctness of the model and the possible impact on human health, further model calibration for a broader temperature range can be undertaken in future research. Tests with heat shocks of 65 °C are currently running and in the near future, tests with a setpoint of 40 and 50 °C are planned.

Secondly, model simulation time (CPU time for integration) is an issue, mainly in models with *Legionella* equations (*e.g*., one single *Legionella* simulation of 17 days (*Figure 11*) was executed, which generated 21 GB of data in a 28 hour simulation and nearly made a powerful computer crash). 9-day simulations proved to be more feasible (*i.e*., 10-12 hour simulations) in terms of simulation time. However for *Legionella* risk analyses, longer simulation periods are necessary. Therefore, Modelica Dymola model optimisations have to be further examined in order to speed up simulations without sacrificing on accuracy and precision.

Furthermore, the *Legionella pneum*. growth model can still be refined. *Legionella pneum*. is a hardly understandable bacteria, with sometimes unexpected growth results (as confirmed by test rig measurements). By further calibration and validation with other casestudies and water temperatures, the growth will become more understandable and controllable. Also additional *Legionella species* and subgroups can be added to the simulation model with different growth curves to verify more than one *Legionella specie* in the DHW and CW system. Future research is currently ongoing.

At last, one of the main reasons, which is thwarting the model development, is that *Legionella* cannot be monitored continuously. *Legionella* samples have to be taken manually, sent to an accredited laboratory and then it takes another week to obtain the *Legionella* results. Furthermore, it is technically impossible to examine tapping samples of one full day (e.g., every hour) for various locations, simply because this requires too much manual labor. Therefore, the limited amount of *Legionella* measurements makes model development much more difficult.

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